Neutrino-oscillation Experiments with the Daya Bay Nuclear Power Facility

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and
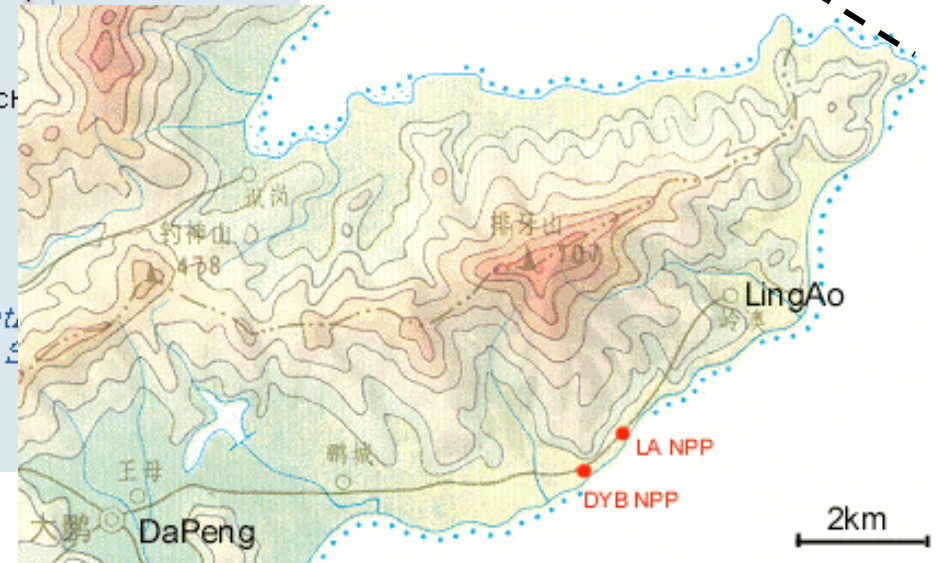*Lawrence Berkeley National Laboratory*

Neutrino Meeting at Santa Fe, October 30, 2005

Location of Daya Bay

- 45 km from Shenzhen

- 55 km from Hong Kong

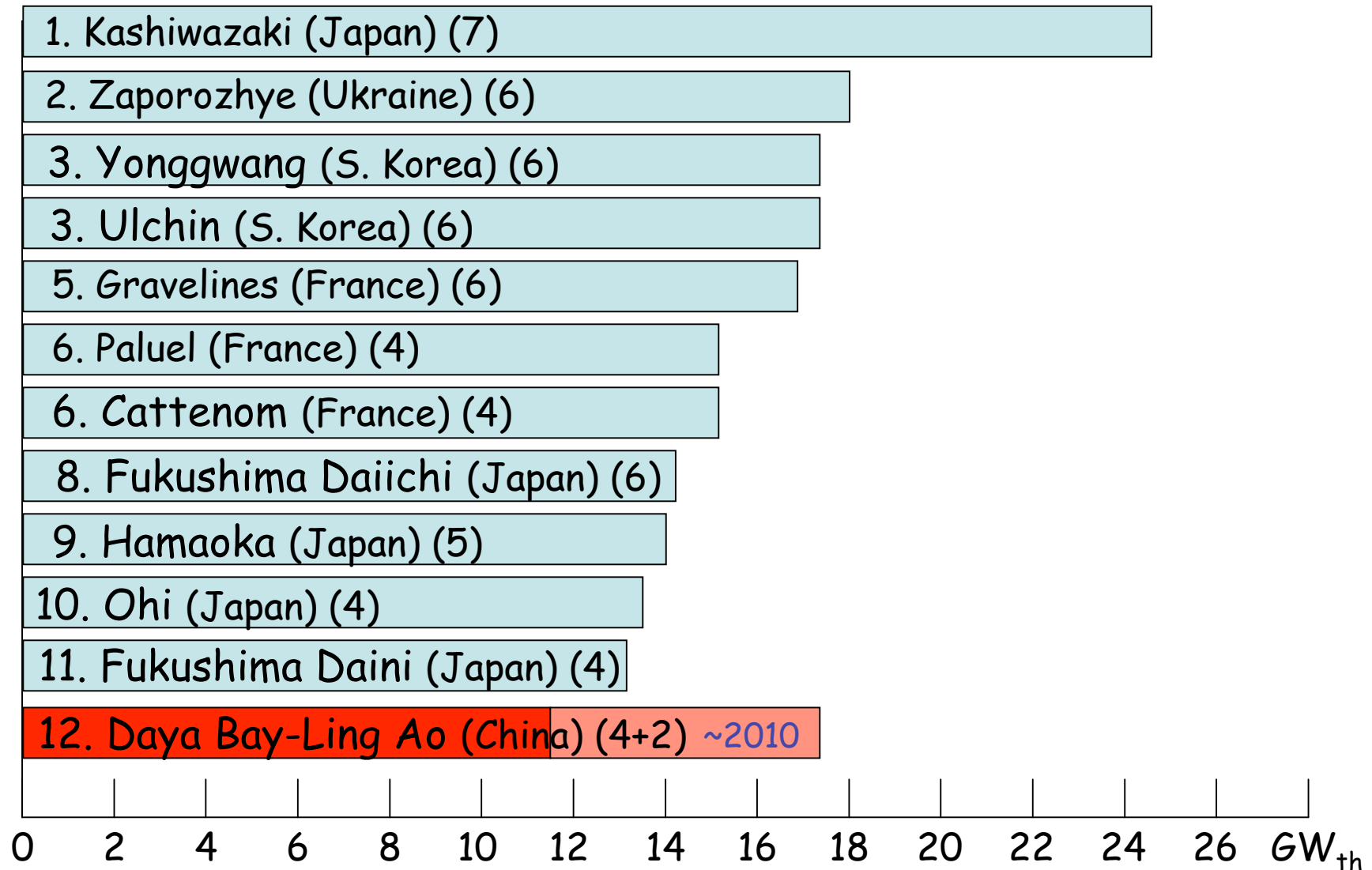The Site

LingAo II NPP:
2×2.9 GW$_{th}$
Ready by 2010

Daya Bay NPP:
2×2.9 GW$_{th}$

LingAo NPP:
2×2.9 GW$_{th}$

Ranking of Reactors

Rank	Reactor	GW$_{th}$
1.	Kashiwazaki (Japan) (7)	
2.	Zaporozhye (Ukraine) (6)	
3.	Yonggwang (S. Korea) (6)	
3.	Ulchin (S. Korea) (6)	
5.	Gravelines (France) (6)	
6.	Paluel (France) (4)	
6.	Cattenom (France) (4)	
8.	Fukushima Daiichi (Japan) (6)	
9.	Hamaoka (Japan) (5)	
10.	Ohi (Japan) (4)	
11.	Fukushima Daini (Japan) (4)	
12.	Daya Bay-Ling Ao (China) (4+2) ~2010	

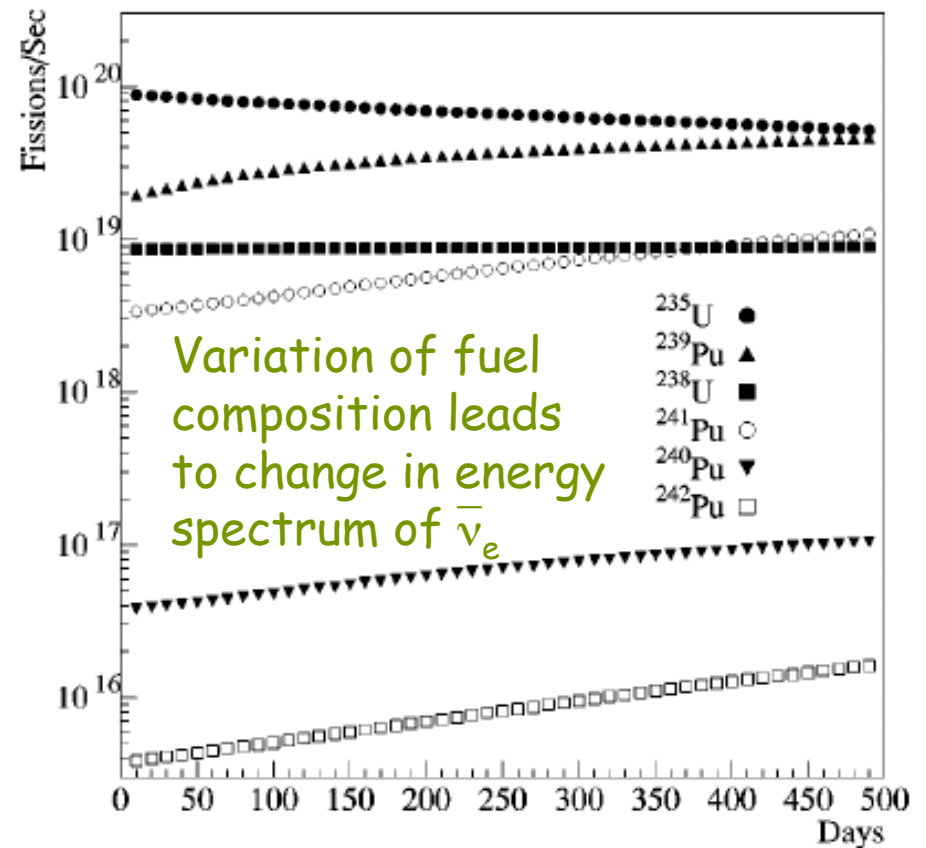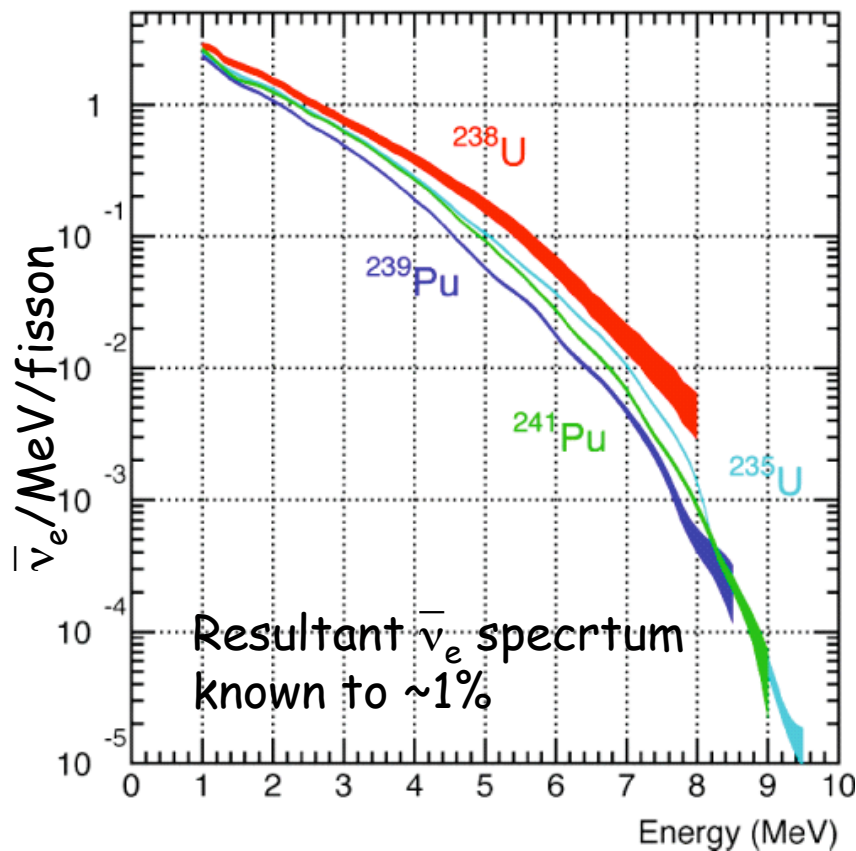0 2 4 6 8 10 12 14 16 18 20 22 24 26 GW$_{th}$

Reactor $\overline{\nu}_e$

- Fission processes in nuclear reactors produce huge number of low-energy $\overline{\nu}_e$:

  3 GW$_{th}$ generates 6×10^{20} $\overline{\nu}_e$ per sec

Resultant $\overline{\nu}_e$ specrtum known to ~1%

Variation of fuel composition leads to change in energy spectrum of $\overline{\nu}_e$

Goals And Approach

- **Utilize the Daya Bay nuclear power facilities to:**

  - determine $\sin^2 2\theta_{13}$ with a sensitivity of 1%
  - measure Δm^2_{31}
  - determine θ_{12} precisely
  - measure Δm^2_{21} as precise as possible

- **Adopt horizontal-access-tunnel scheme:**

  - mature and relatively inexpensive technology
  - flexible in choosing overburden
  - relatively easy and cheap to add expt. halls
  - easy access to underground experimental facilities
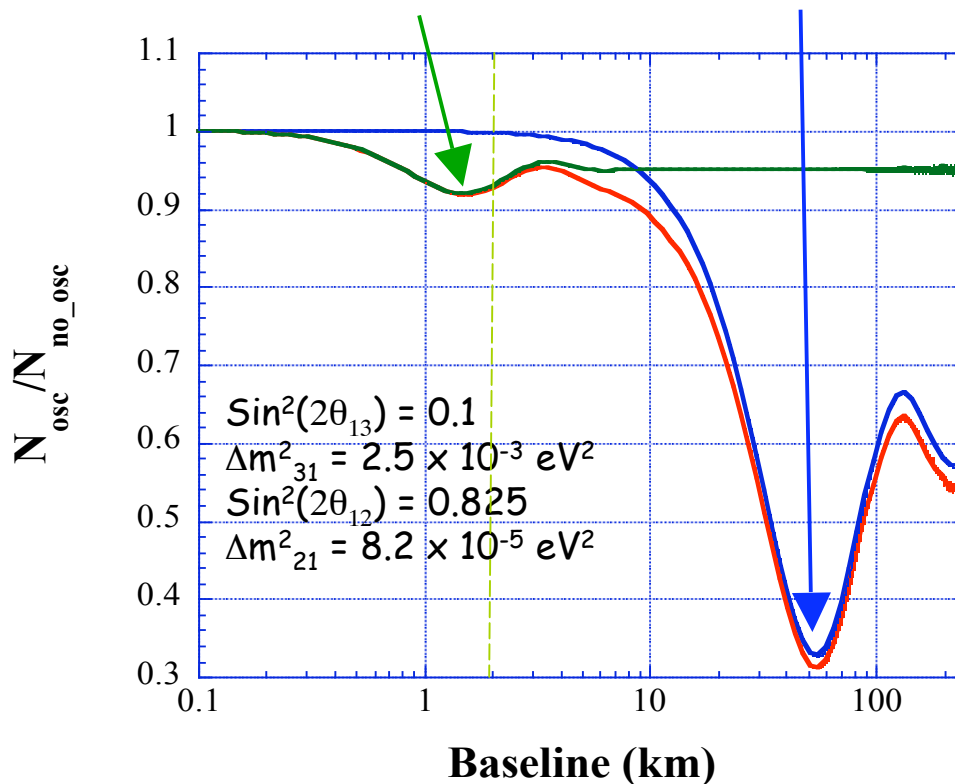 - easy to move detectors between different locations with good environmental control.

The Daya Bay Experiment:
Determination of θ_{13} and Δm^2_{31}
A China-Russia-US Collaboration

Where To Place The Detectors ?

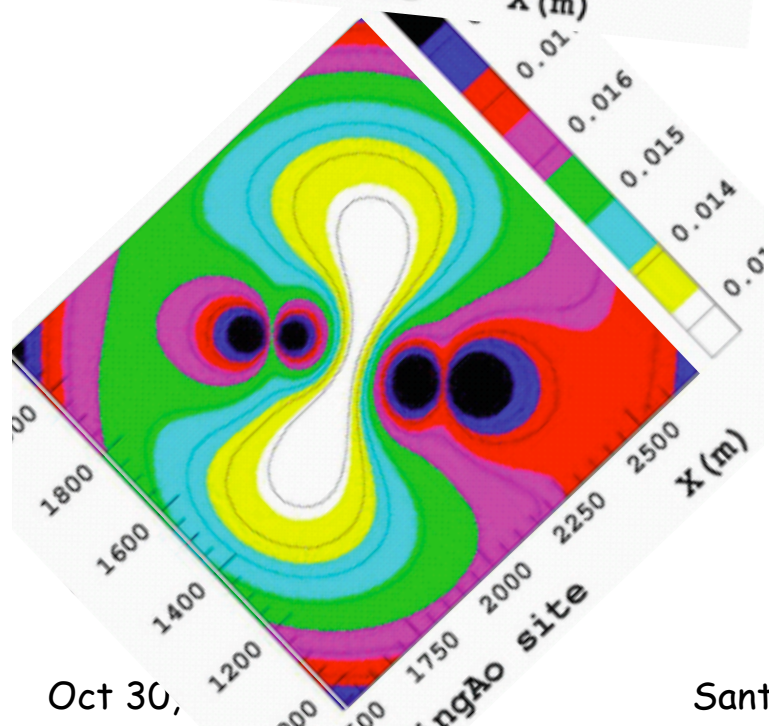- Since reactor $\bar{\nu}_e$ are low-energy, it is a disappearance experiment:
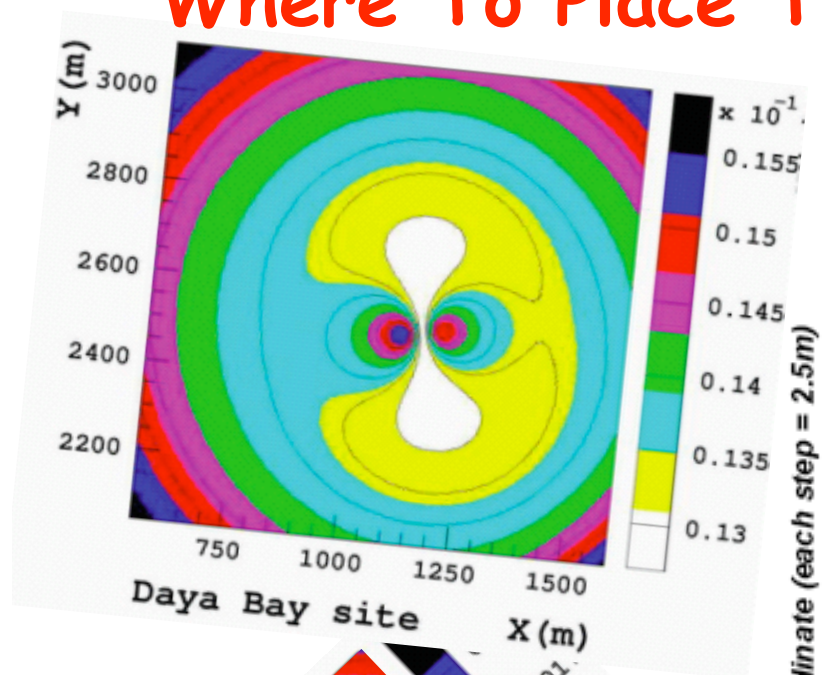
$$P(\bar{\nu}_e \rightarrow \bar{\nu}_e) \approx 1 - \sin^2 2\theta_{13} \sin^2\left(\frac{\Delta m_{31}^2 L}{4E}\right) - \cos^4 \theta_{13} \sin^2 2\theta_{12} \sin^2\left(\frac{\Delta m_{21}^2 L}{4E}\right)$$

Small-amplitude oscillation due to θ_{13}

Large-amplitude oscillation due to θ_{12}

$Sin^2(2\theta_{13}) = 0.1$
$\Delta m^2_{31} = 2.5 \times 10^{-3}$ eV²
$Sin^2(2\theta_{12}) = 0.825$
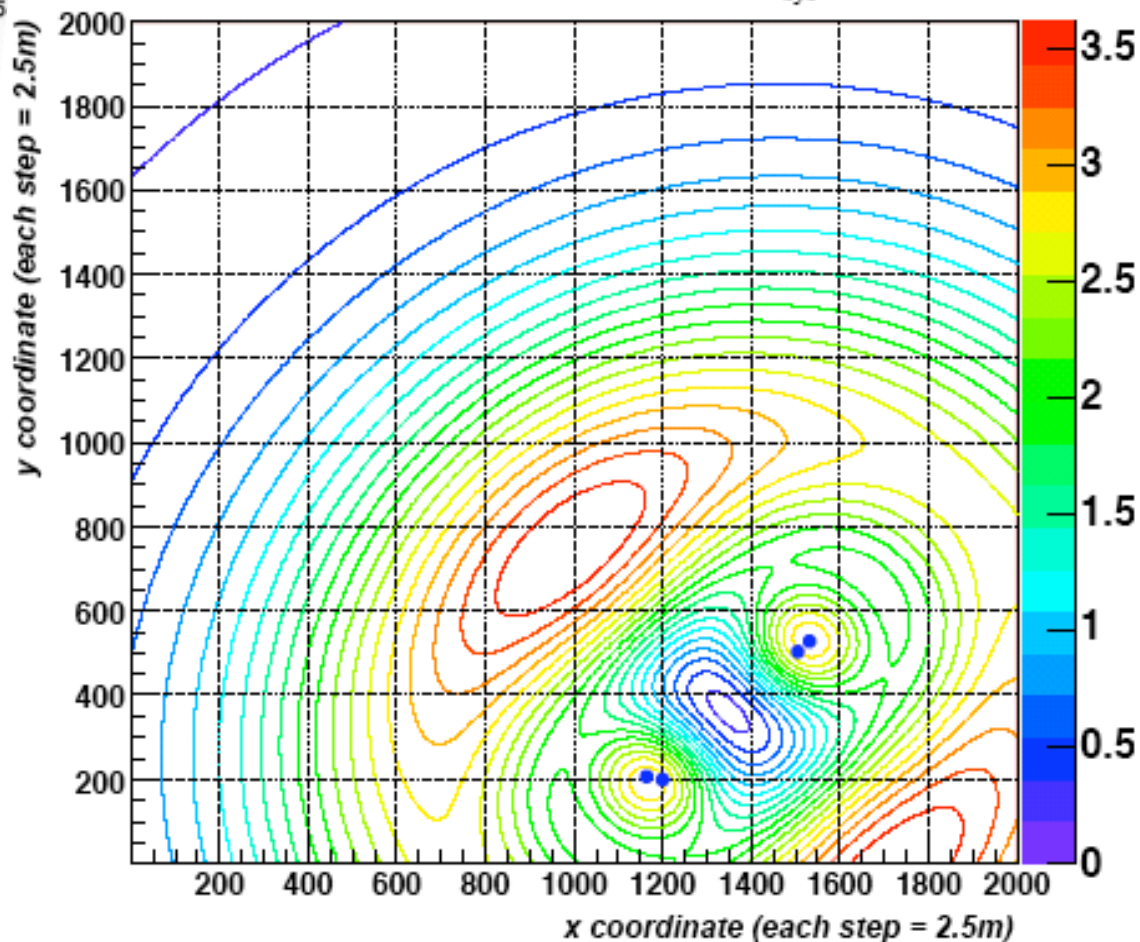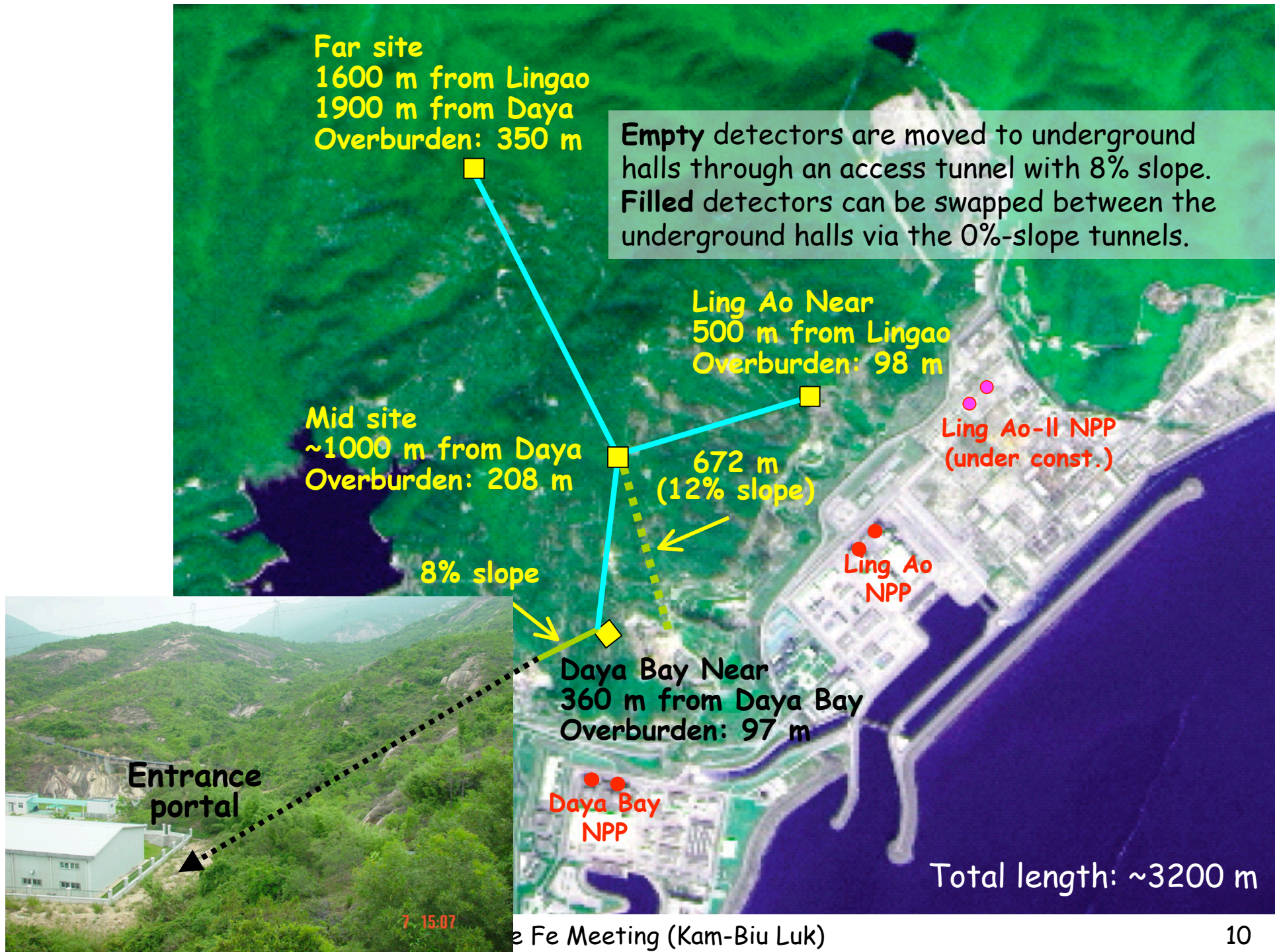$\Delta m^2_{21} = 8.2 \times 10^{-5}$ eV²

N_{osc}/N_{no_osc}

Baseline (km)

- Place near detector(s) close to reactor(s) to measure raw flux and spectrum of $\bar{\nu}_e$, reducing reactor-related systematic

- Position a far detector near the first oscillation maximum to get the highest sensitivity, and also be less affected by θ_{12}

Where To Place The Detectors At Daya Bay?

χ^2 contour plot for $\Delta m^2 = 2.5 \times 10^{-3} eV^2$
near detector baseline = 500m, with $\sigma_{sys} = 0.5\%$

Far site
1600 m from Lingao
1900 m from Daya
Overburden: 350 m

Empty detectors are moved to underground halls through an access tunnel with 8% slope. **Filled** detectors can be swapped between the underground halls via the 0%-slope tunnels.

Ling Ao Near
500 m from Lingao
Overburden: 98 m

Ling Ao-II NPP
(under const.)

Mid site
~1000 m from Daya
Overburden: 208 m

672 m
(12% slope)

Ling Ao
NPP

8% slope

Daya Bay Near
360 m from Daya Bay
Overburden: 97 m

Entrance
portal

Daya Bay
NPP

Total length: ~3200 m

A Versatile Site

- **Rapid deployment:**
  - Daya near site + mid site
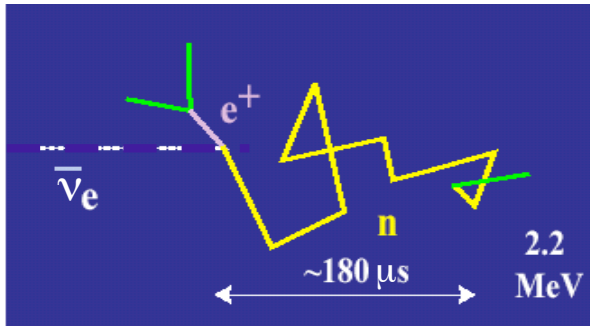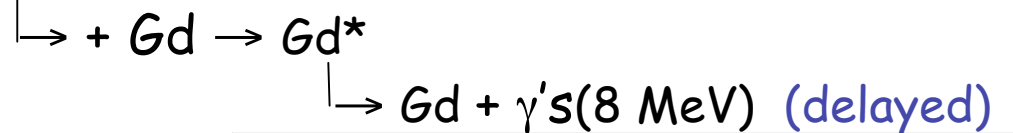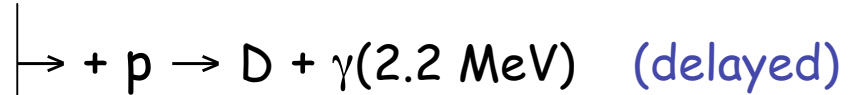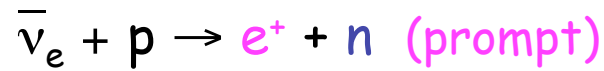 - 0.7% reactor systematic error

- **Full operation:**
  - (1) Two near sites + Far site
  - (2) Mid site + Far site
  - (3) Two near sites + Mid site + Far site

  Internal checks, each with different systematic
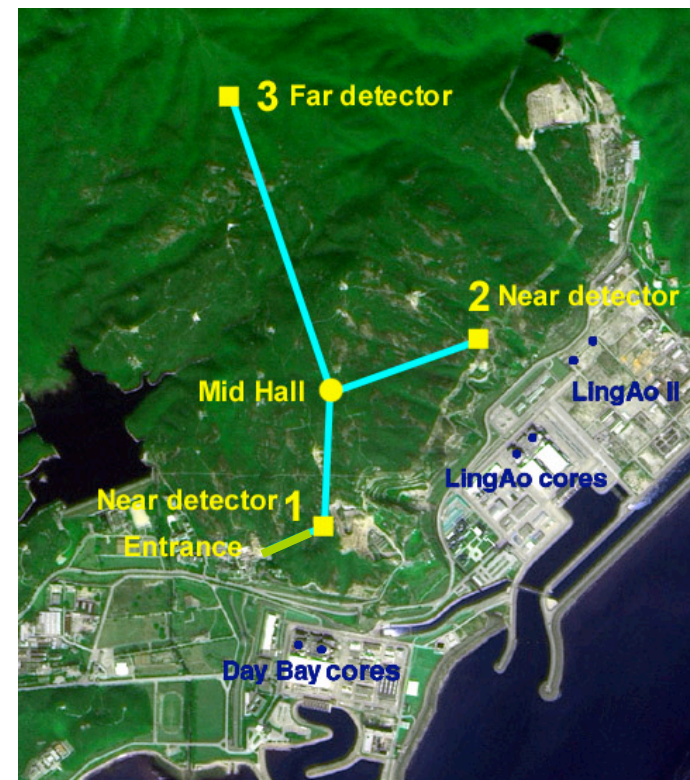
Detecting Low-energy $\bar{\nu}_e$

- The reaction is the inverse β-decay in Gd-doped liquid scintillator:

$$\bar{\nu}_e + p \rightarrow e^+ + n \quad \text{(prompt)}$$

$$\rightarrow + p \rightarrow D + \gamma(2.2 \text{ MeV}) \quad \text{(delayed)}$$

$$\rightarrow + Gd \rightarrow Gd^*$$

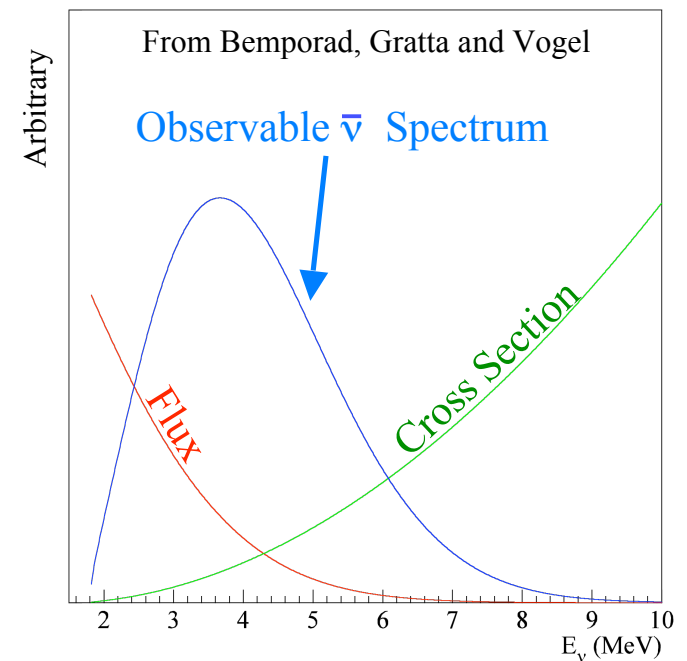$$\rightarrow Gd + \gamma\text{'s}(8 \text{ MeV}) \quad \text{(delayed)}$$

- Time- and energy-tagged signal is a good tool to suppress background events.
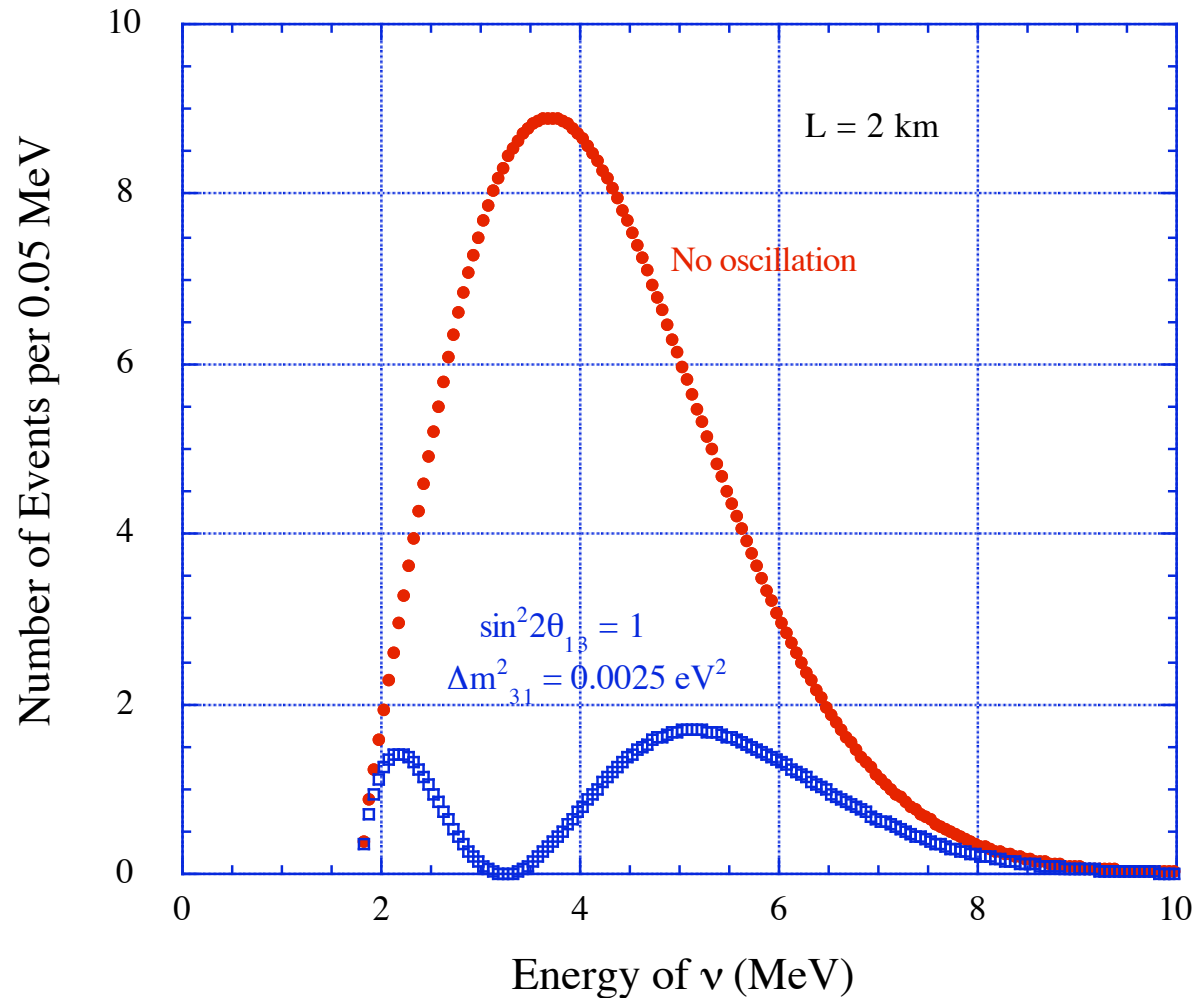
- Energy of $\bar{\nu}_e$ is given by:

$$E_{\bar{\nu}} \approx T_{e+} + T_n + (m_n - m_p) + m_{e+} \approx T_{e+} + 1.8 \text{ MeV}$$

10-40 keV

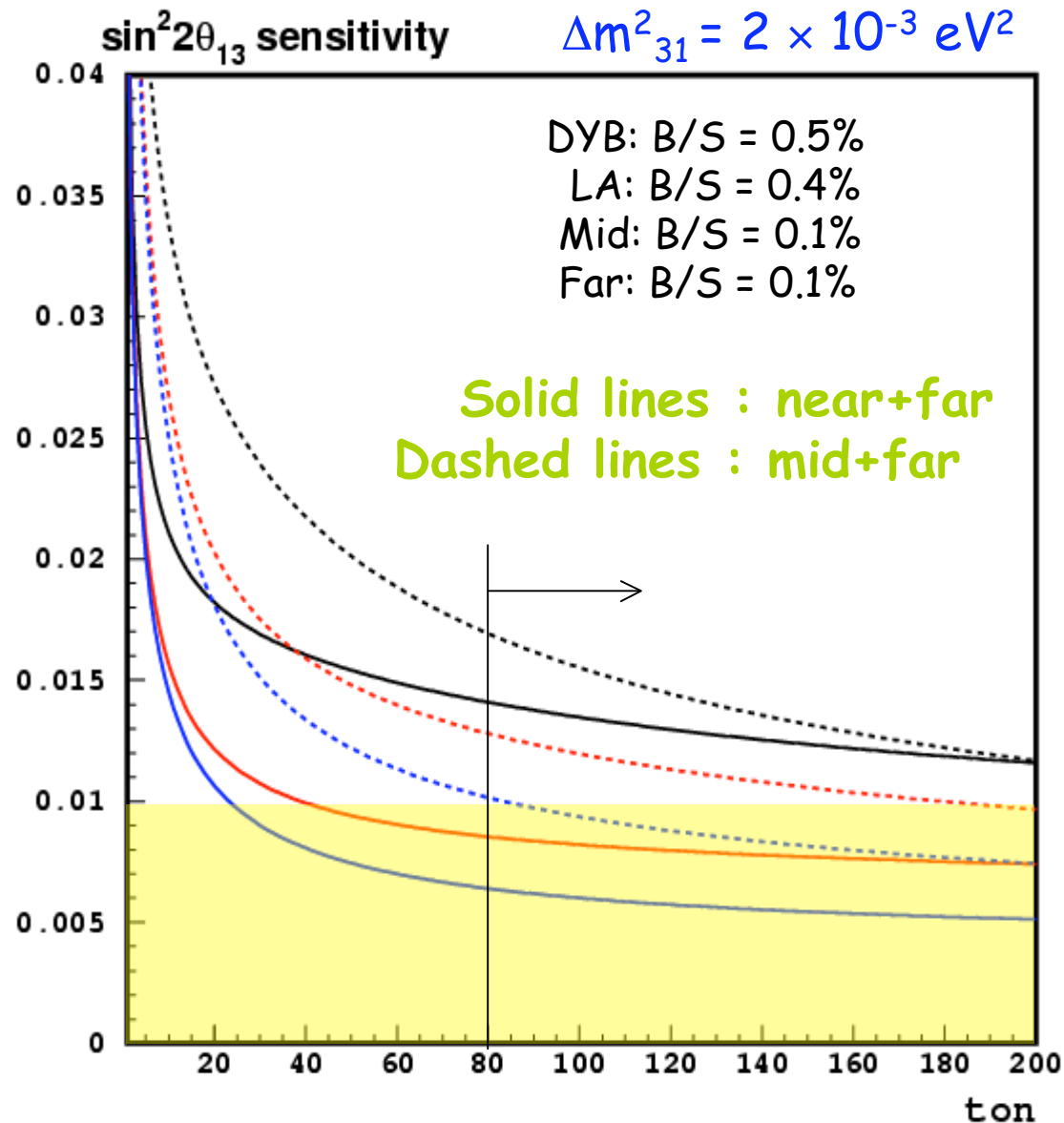- Threshold of inverse β-decay is about 1.8 MeV; thus only about 25% of the reactor $\bar{\nu}_e$ is usable.

From Bemporad, Gratta and Vogel

Observable $\bar{\nu}$ Spectrum

Arbitrary

Flux

Cross Section

E_ν (MeV)

How To Measure θ_{13} With Reactor $\bar{\nu}_e$?

1. **Rate deficit**: deviation from $1/r^2$ expectation
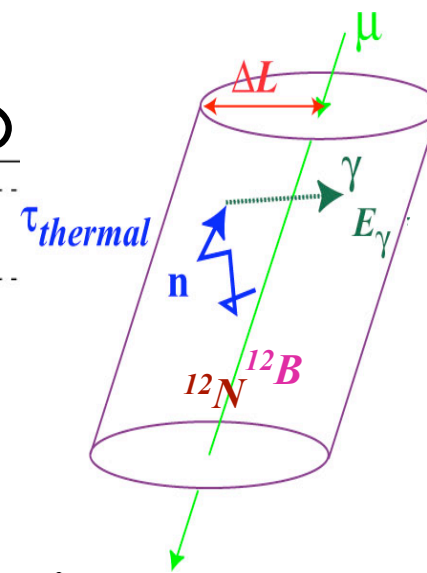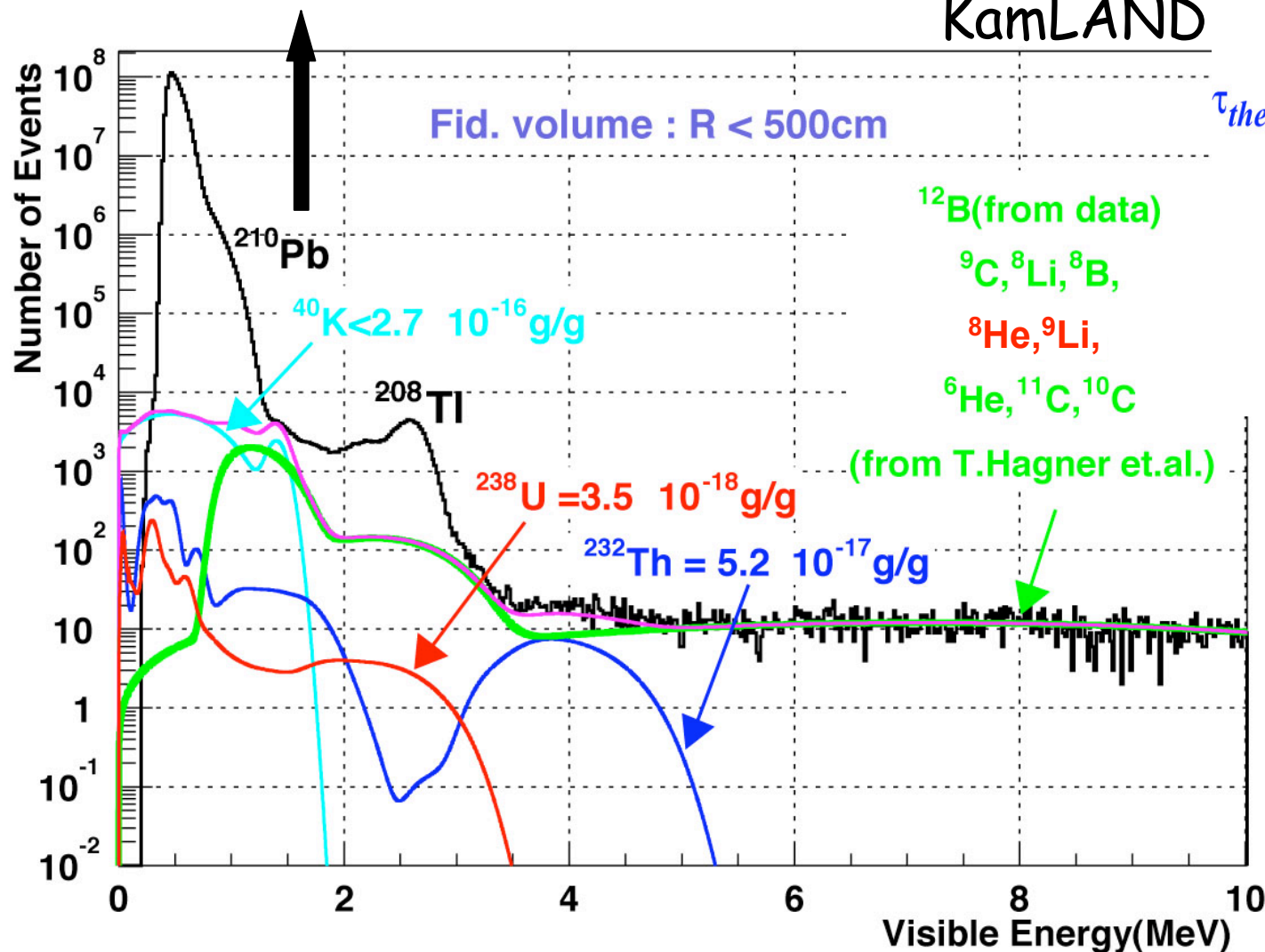2. **Spectral distortion**

What Target Mass Should Be?

sin$^2 2\theta_{13}$ sensitivity $\Delta m^2_{31} = 2 \times 10^{-3}$ eV^2

DYB: B/S = 0.5%
LA: B/S = 0.4%
Mid: B/S = 0.1%
Far: B/S = 0.1%

Solid lines : near+far
Dashed lines : mid+far

Systematic error (per site):
Black : 0.6%
Red : 0.25%
Blue : 0.12%

ton

Beat The Background

Keep everything as pure as possible!

KamLAND

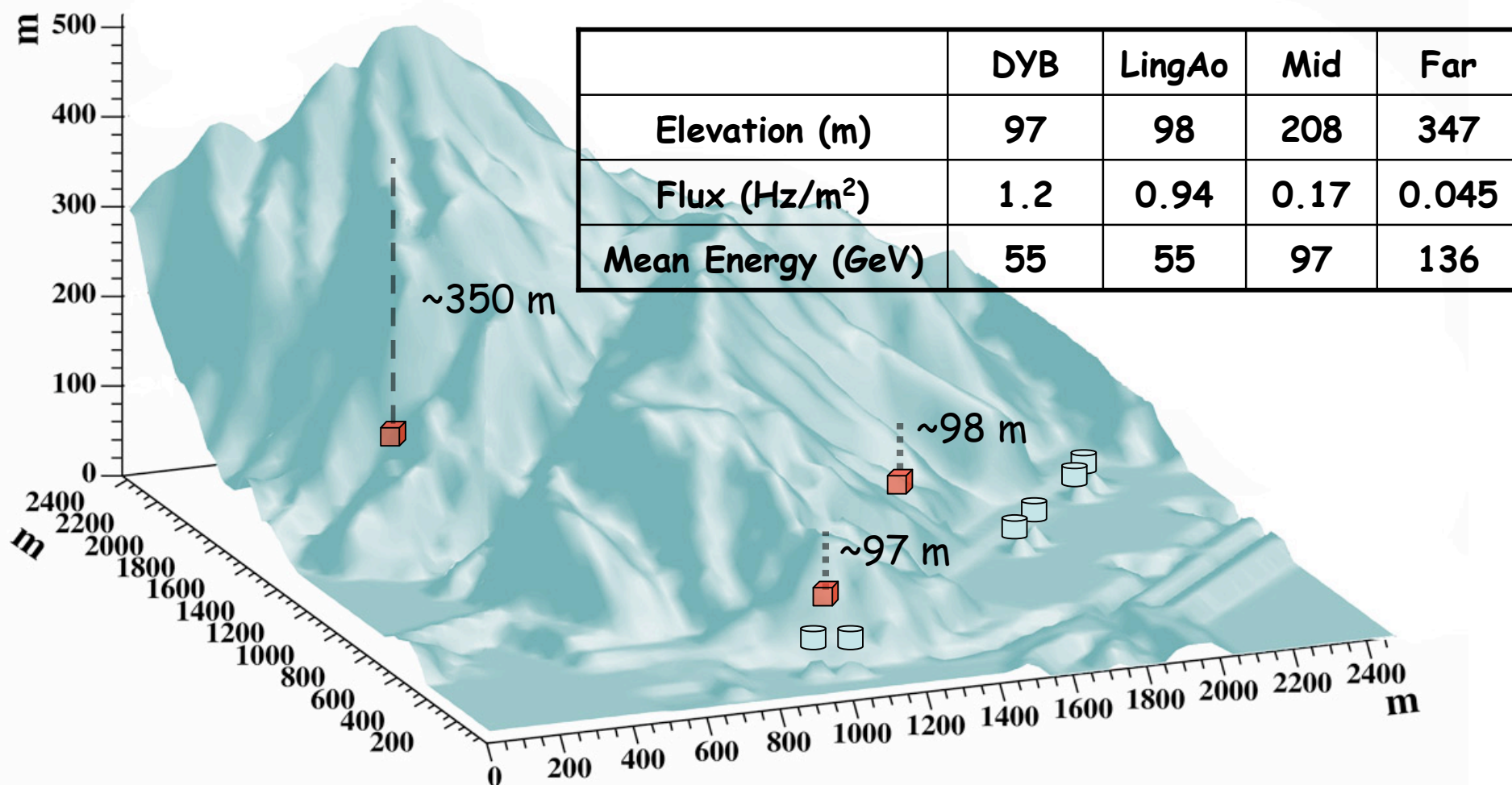Fid. volume : R < 500cm

^{210}Pb

^{40}K < 2.7 10^{-16} g/g

^{208}Tl

^{238}U = 3.5 10^{-18} g/g

^{232}Th = 5.2 10^{-17} g/g

^{12}B(from data)

^{9}C, ^{8}Li, ^{8}B,

^{8}He, ^{9}Li,

^{6}He, ^{11}C, ^{10}C

(from T.Hagner et.al.)

Depends on the flux of cosmic muons in the vicinity of the detector

μ

ΔL

γ

E_{γ}

$\tau_{thermal}$

n

^{12}N ^{12}B

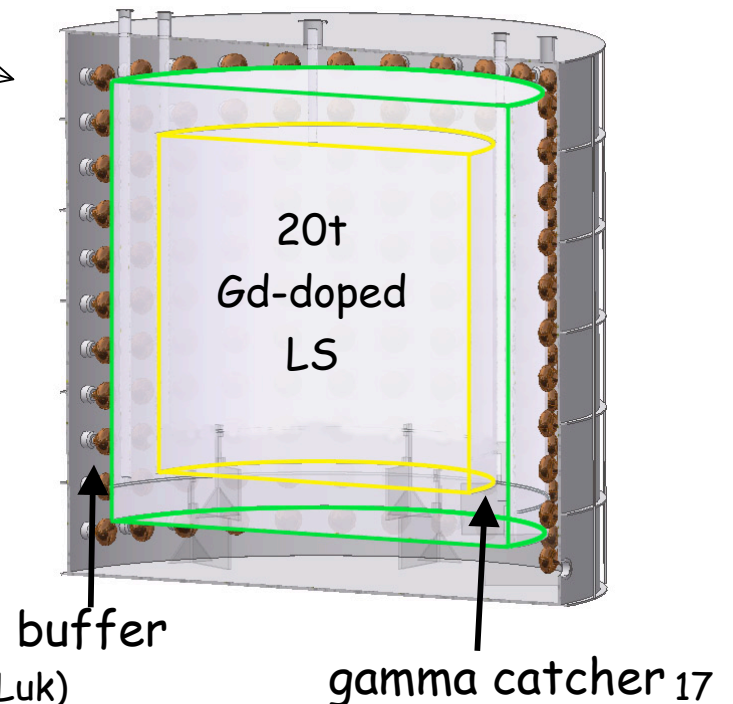Number of Events

Visible Energy(MeV)

Cosmic-ray Muon
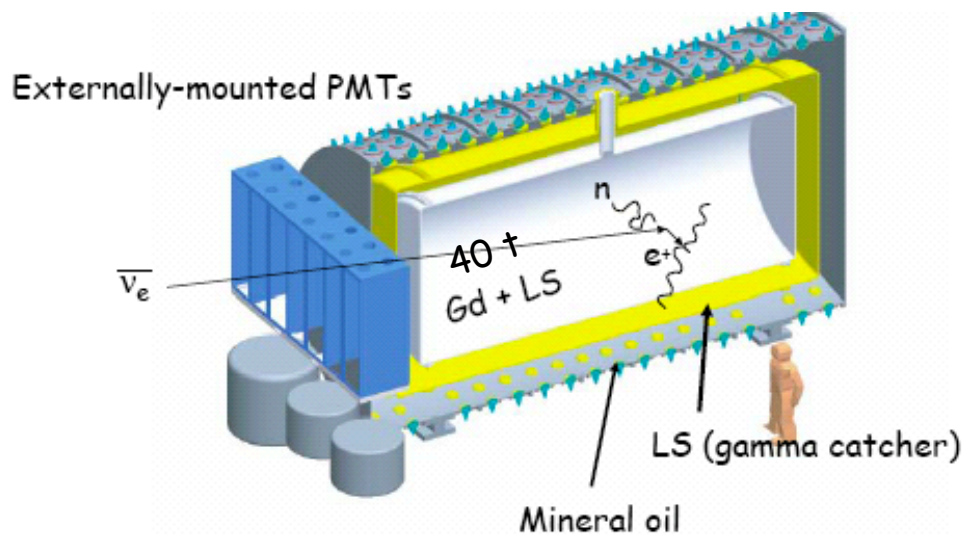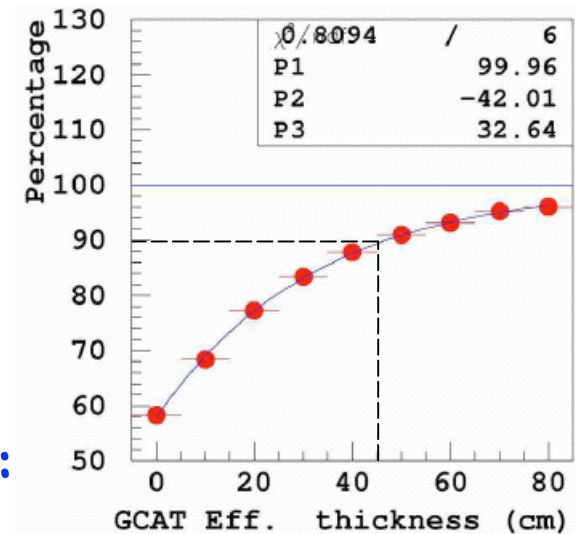
- Apply the Geiser parametrization for cosmic-ray flux at surface
- Use MUSIC and mountain profile to estimate muon flux & energy

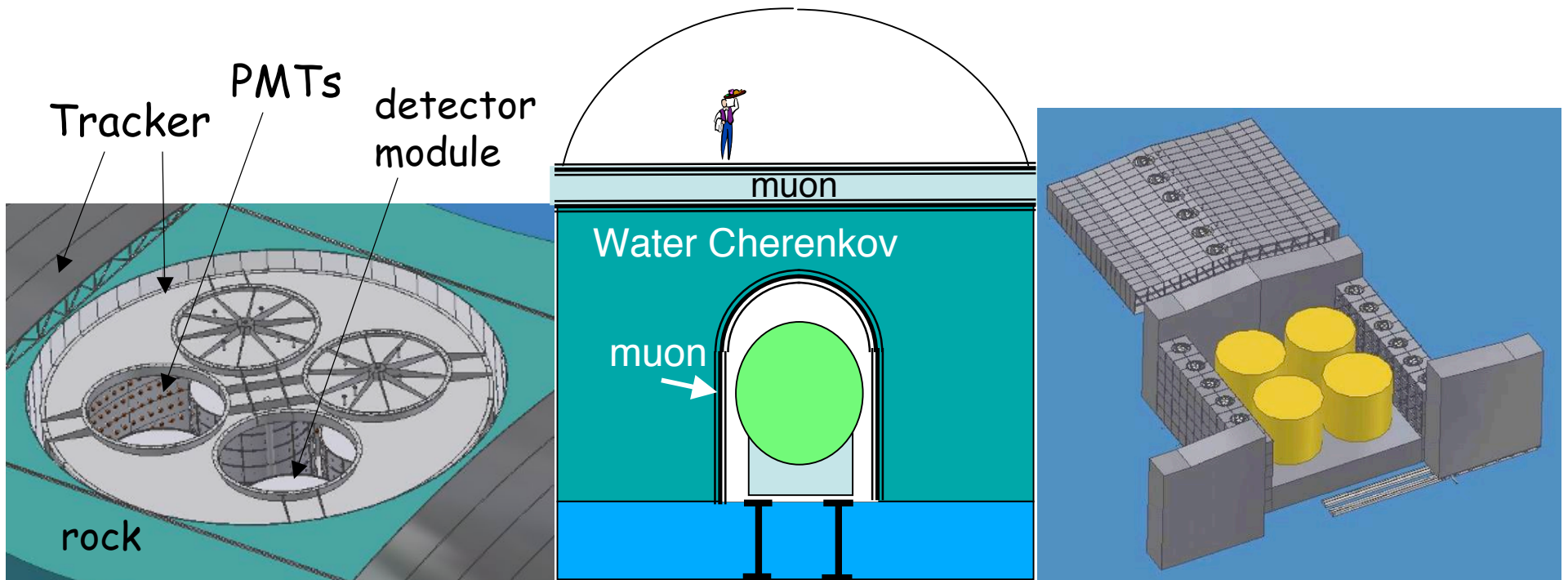|	DYB	LingAo	Mid	Far
Elevation (m)	97	98	208	347
Flux (Hz/m^2)	1.2	0.94	0.17	0.045
Mean Energy (GeV)	55	55	97	136

~350 m

~98 m

~97 m

Conceptual Design of Detector Modules

- **Three-layer structure**:
  - I.   Target: Gd-loaded liquid scintillator
  - II. Gamma catcher: liquid scintillator, 45cm
  - III. Buffer shielding: mineral oil, ~45cm

- Possibly with diffuse reflection at ends. For ~200 PMT's around the barrel:

$$\frac{\sigma}{E} \sim \frac{14\%}{\sqrt{E(\text{MeV})}}, \quad \sigma_{vertex} = 14\text{cm}$$

Externally-mounted PMTs

$\overline{\nu_e}$

40 t Gd + LS

n

e+

LS (gamma catcher)

Mineral oil

20t Gd-doped LS

buffer

gamma catcher

Conceptual Design of Shield-Muon Veto

- Detector modules enclosed by 2m+ of water to shield neutrons and gamma-rays from surrounding rock
- Water shield also serves as a Cherenkov veto
- Augmented with a muon tracker: scintillator strips or RPCs
- Combined efficiency of Cherenkov and tracker > 99.5%

Background

- **Natural Radioactivity**: PMT glass, Rock, Radon in the air, etc

- **Slow neutron, and fast neutron**

  - Neutrons produced in rock and water shielding (99.5% veto efficiency)

- **Cosmogenic isotopes: ^{8}He/^{9}Li which can β-n decay**

  - Cross section measured at CERN (Hagner et. al.)

  - Can be measured in-situ, even for near detector with muon rate ~ 10 Hz.

- **Use a modified Palo-Verde-Geant3-based MC to model response of detector:**

	Near Site	Far Site
Radioactivity (Hz)	<50	<50
Accidental B/S	<0.05%	<0.05%
Fast Neutron background B/S	0.15%	0.1%
^{8}He/^{9}Li B/S	0.55%	0.25%

The above number is before shower-muon cut.
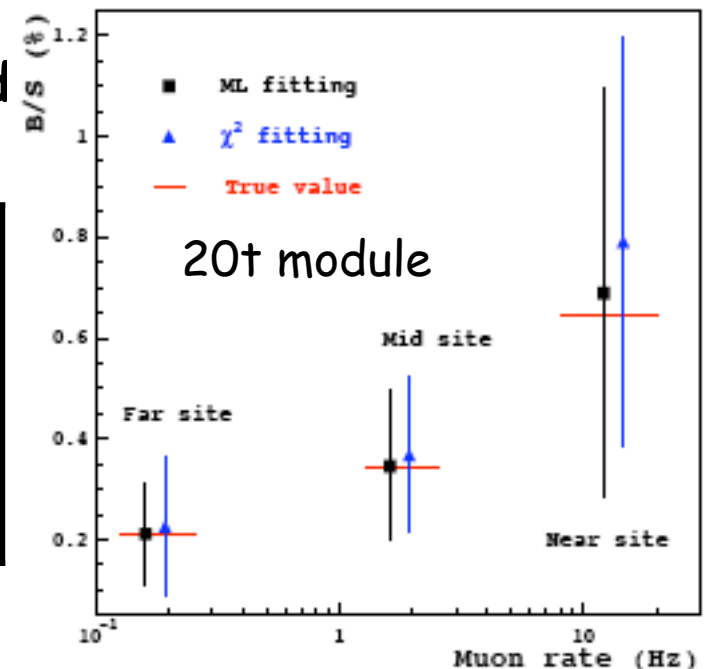
Systematic Uncertainty

| Systematic error	Chooz	Daya Bay
Reaction Cross Section	1.9%	0, near-far cancellation
Energy released per fission	0.6%	0, near-far cancellation
Reactor Power	0.7%	0.06%, near-far cancellation
Number of Protons	0.8%	0, detector swapping
Detection efficiency*	1.5%	~0.2%, fewer cuts, detector swapping
Total	2.75%	~0.2%

*

- No Vertex cut.
- Residual detection error is dominated by the **neutron energy cut** at 6 MeV - arises mainly from the energy-scale uncertainties. It is ~0.2% for a 1% energy-scale error at 6 MeV.
- **Positron energy cut** is negligible.

> Statistical Error (3 years):   0.2%
> Residual systematic error: ~ 0.2%
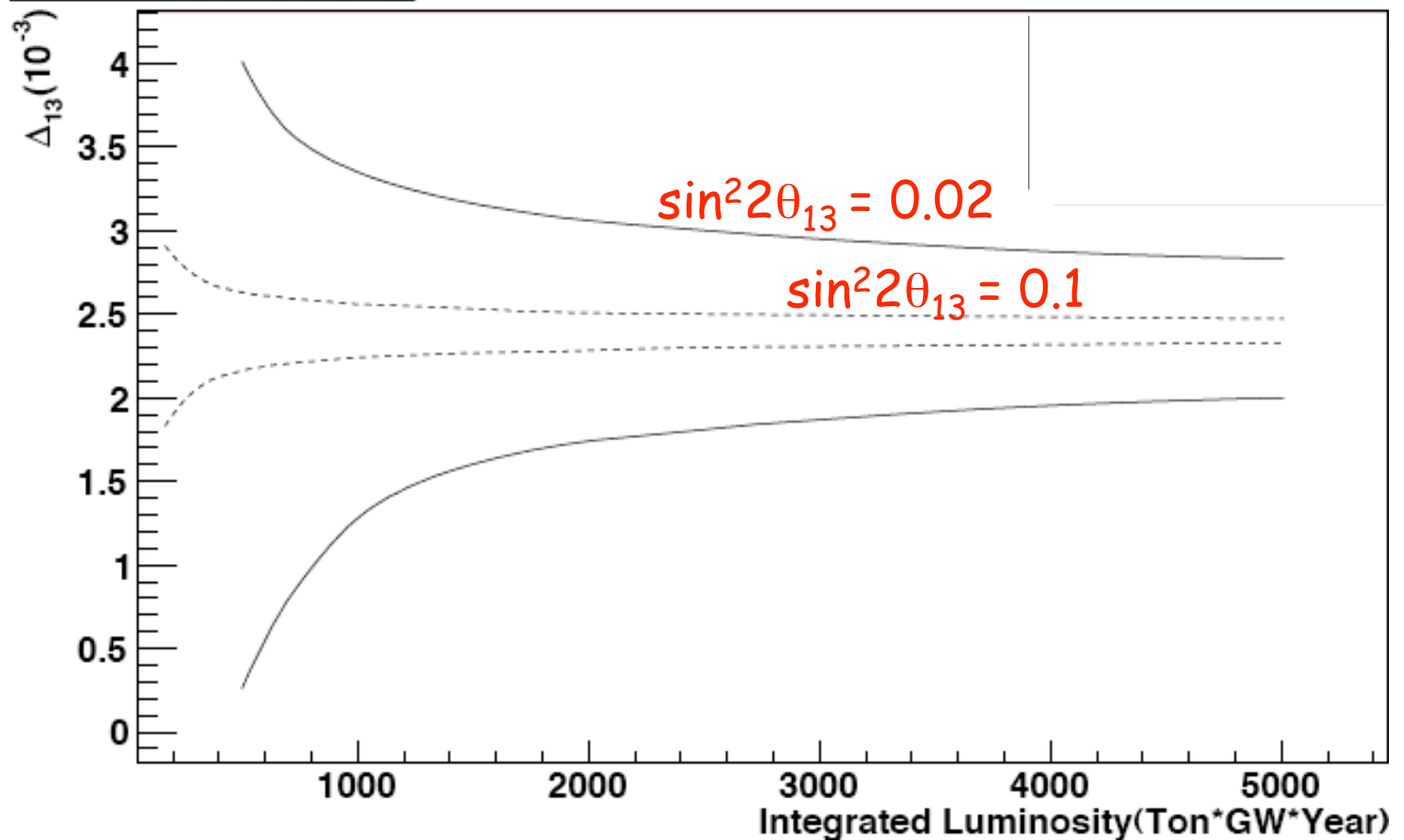> Background: B/S ~ 0.6%

Sensitivity of $\sin^2 2\theta_{13}$

- Daya Bay site
  - baseline = 360 m
  - target mass = 40 ton
  - B/S = ~0.5%

- LingAo site
  - baseline = 500 m
  - target mass = 40 ton
  - B/S = ~0.5%

- Far site
  - baseline = 1900 m to DYB cores
    1600 m to LA cores
  - target mass = 80 ton
  - B/S = ~0.2%

- Three-year run (0.2% statistical error)

- Detector residual error = 0.2%

- Use rate and spectral shape

90% confidence level
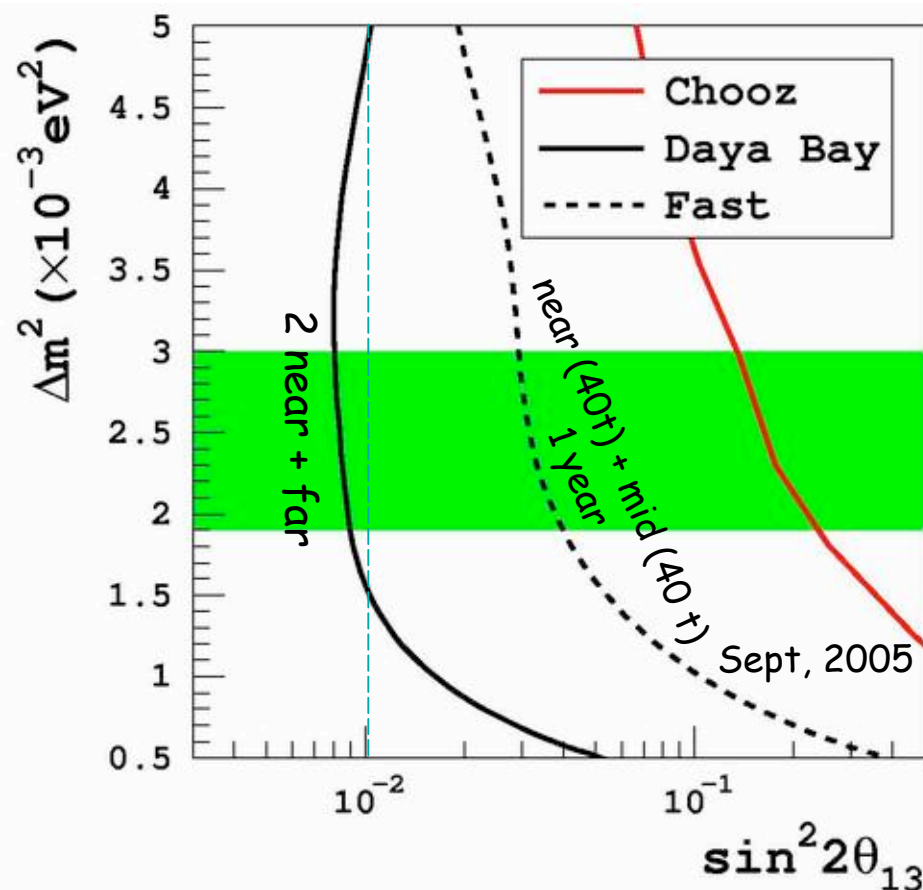
Precision of Δm^2_{31}

Geotechnical Survey

- Topography survey: Completed
- Geological Survey: Completed
  - Verified topographic information
  - Generated new map covering 7.5 km^2
- Geological Physical Survey: Completed
  - High-resolution electric resistance
  - Seismic
  - Micro-gravity
- Bore-Hole Drilling: November-December, 2005
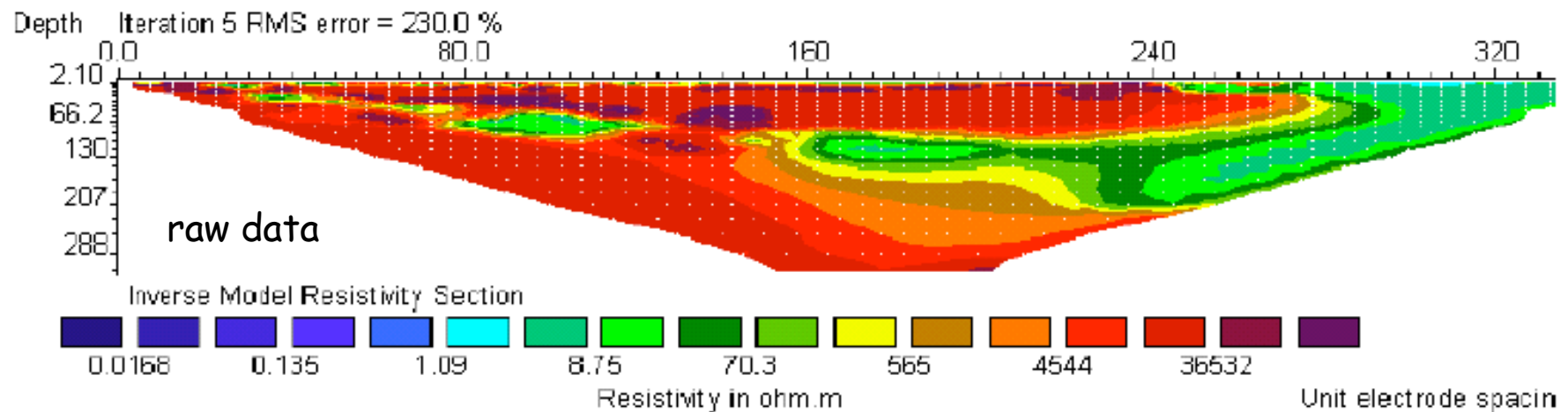
Synthesis of Gd-loaded Liquid Scintillator

- Investigating a few candidates at IHEP:

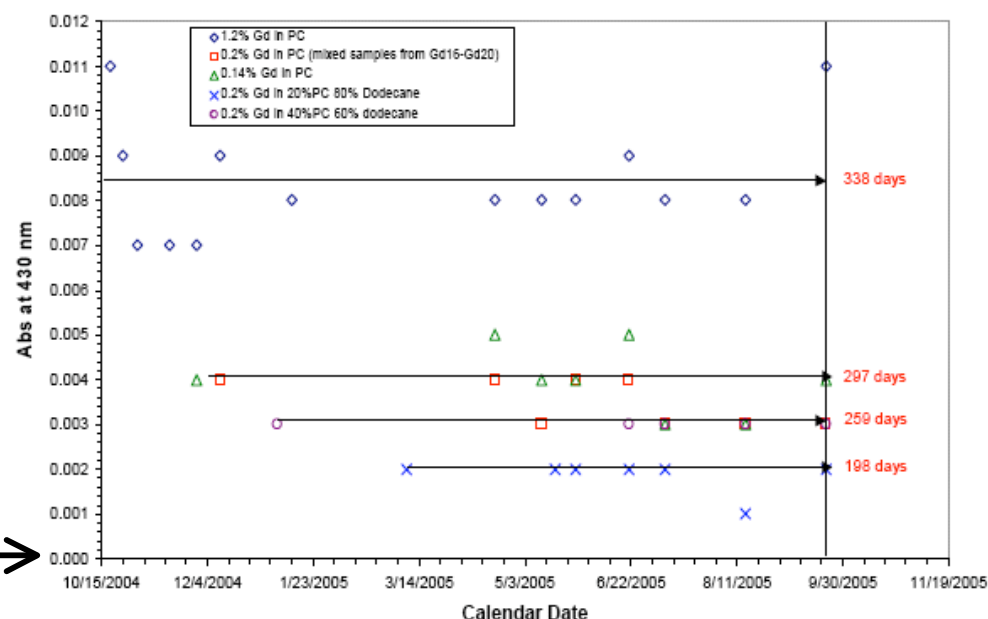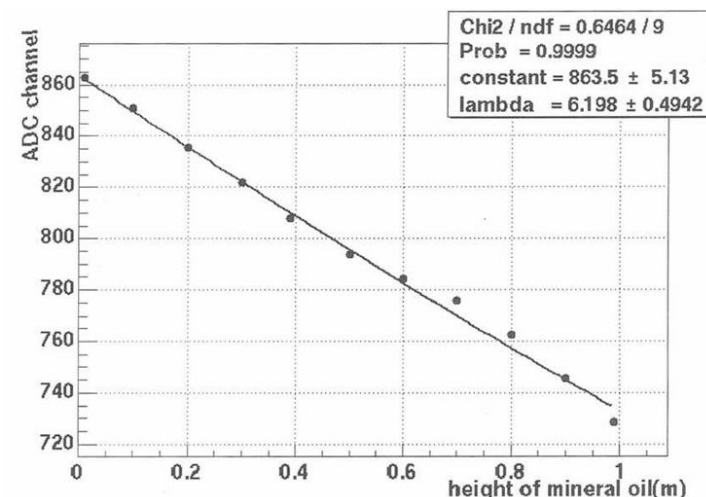 One candidate:

  - 0.1% Gd (D2EHP-ligand) in

    20% mesitylene-80% dodecane

  - Light yield: 91% of pure LS

  - attenuation length = 6.2 m

  - stable for more than two months:

| Date	2005. 06.13	2005. 08.01	2005. 08.26
Gd (%)	0.1	0.098	0.1

  - no effect on acrylic

- R&D collaborative effort at BNL:
  - Gd (carboxylate ligands) in PC and dodecane
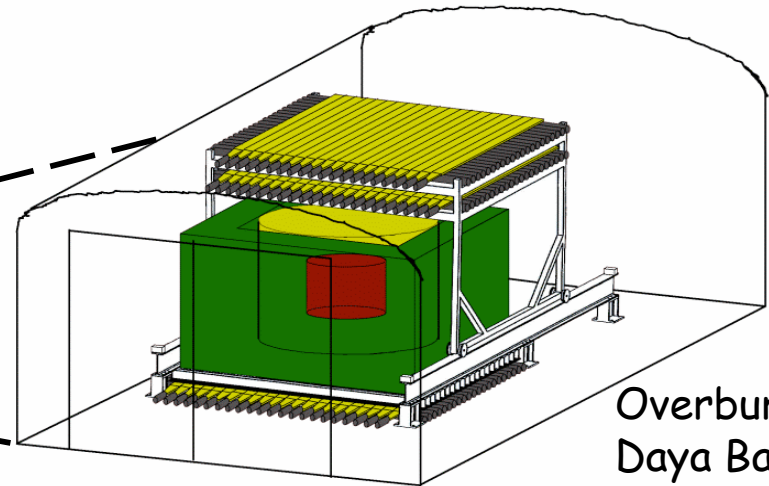 - all stable for almost a year

Prototype Detector at IHEP

- Constructing a 2-layer prototype with 0.5 t Gd-doped LS enclosed in 5 t of mineral oil, and 45 8" PMTs to evaluate design issues at IHEP, Beijing
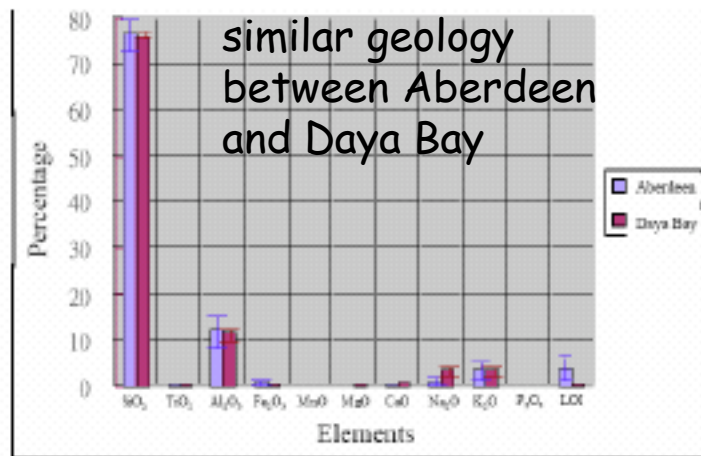

PMT mount

Steel tank

acrylic vessel

Front-end board (version 2)
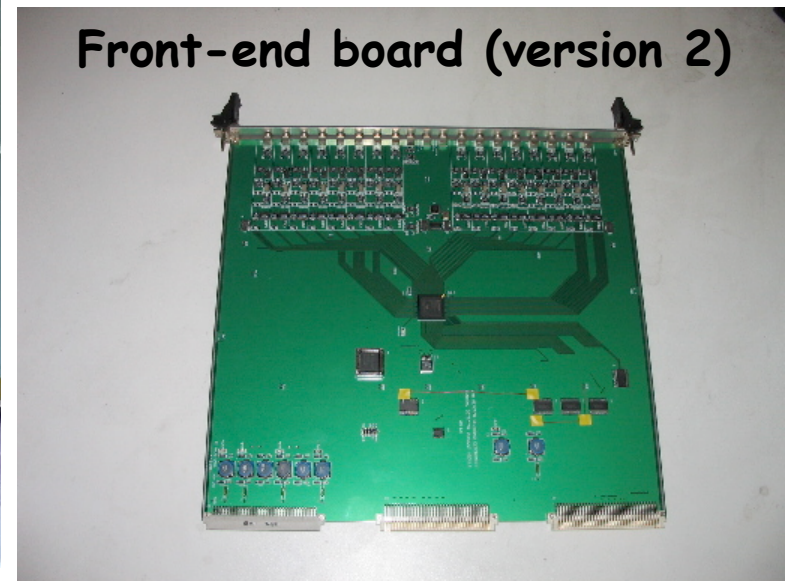
The Aberdeen Tunnel Experiment

• Study cosmic muons & cosmogenic background in Aberdeen Tunnel, Hong Kong.

Overburden ~ Daya Bay sites

similar geology between Aberdeen and Daya Bay

Fig. 1 A comparison of rock compositions at Daya Bay and Aberdeen.
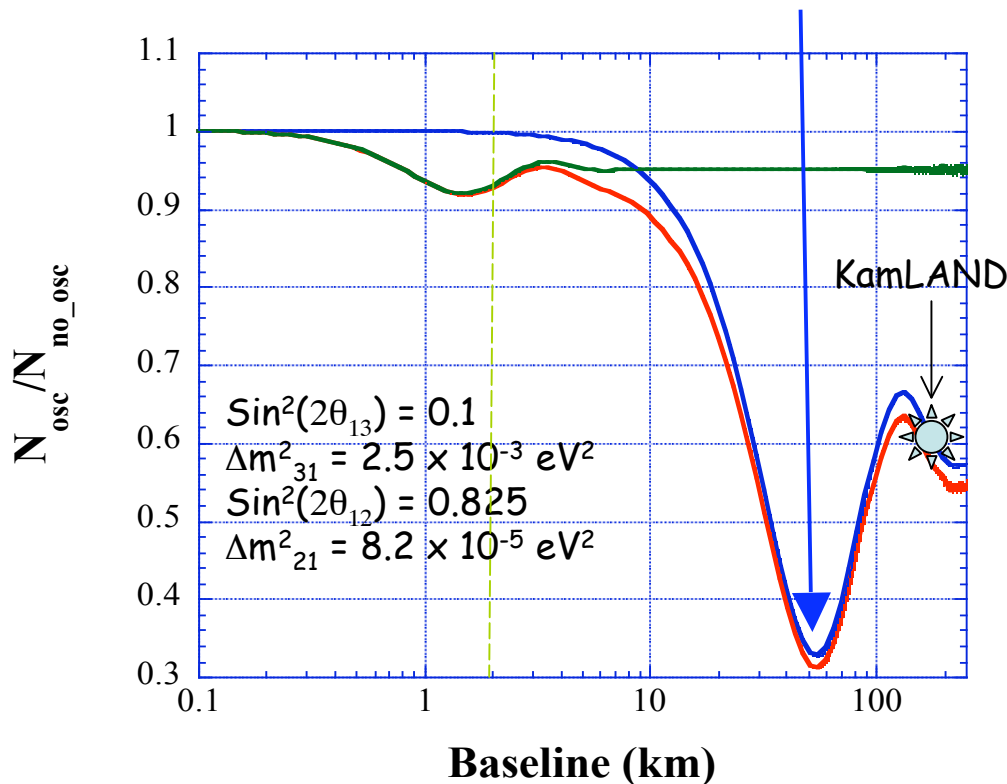
Installing proptubes in Sept, 2005

Precision Measurement of θ_{12} and Δm^2_{21}
HKU, CUHK, and Berkeley

Precise Measurement of θ_{12}

- Since reactor $\bar{\nu}_e$ are low-energy, it is a disappearance experiment:

$$P(\bar{\nu}_e \to \bar{\nu}_e) \approx 1 - \sin^2 2\theta_{13}\sin^2\left(\frac{\Delta m_{31}^2 L}{4E}\right) - \cos^4\theta_{13}\sin^2 2\theta_{12}\sin^2\left(\frac{\Delta m_{21}^2 L}{4E}\right)$$

Large-amplitude oscillation
at ~55 km due to θ_{12}

$\text{Sin}^2(2\theta_{13}) = 0.1$
$\Delta m_{31}^2 = 2.5 \times 10^{-3}\ eV^2$
$\text{Sin}^2(2\theta_{12}) = 0.825$
$\Delta m_{21}^2 = 8.2 \times 10^{-5}\ eV^2$

KamLAND

- **Near detectors** close to reactors measure raw flux and spectrum of $\bar{\nu}_e$, reducing reactor-related systematic

- Position a **far detector** near the first oscillation maximum to get the highest sensitivity of θ_{12}

Location of Hong Kong Site For θ_{12} Measurement

Daya Bay NPP

Shenzhen

~55 km

Tai Mo Shan (957 m)

Hong Kong
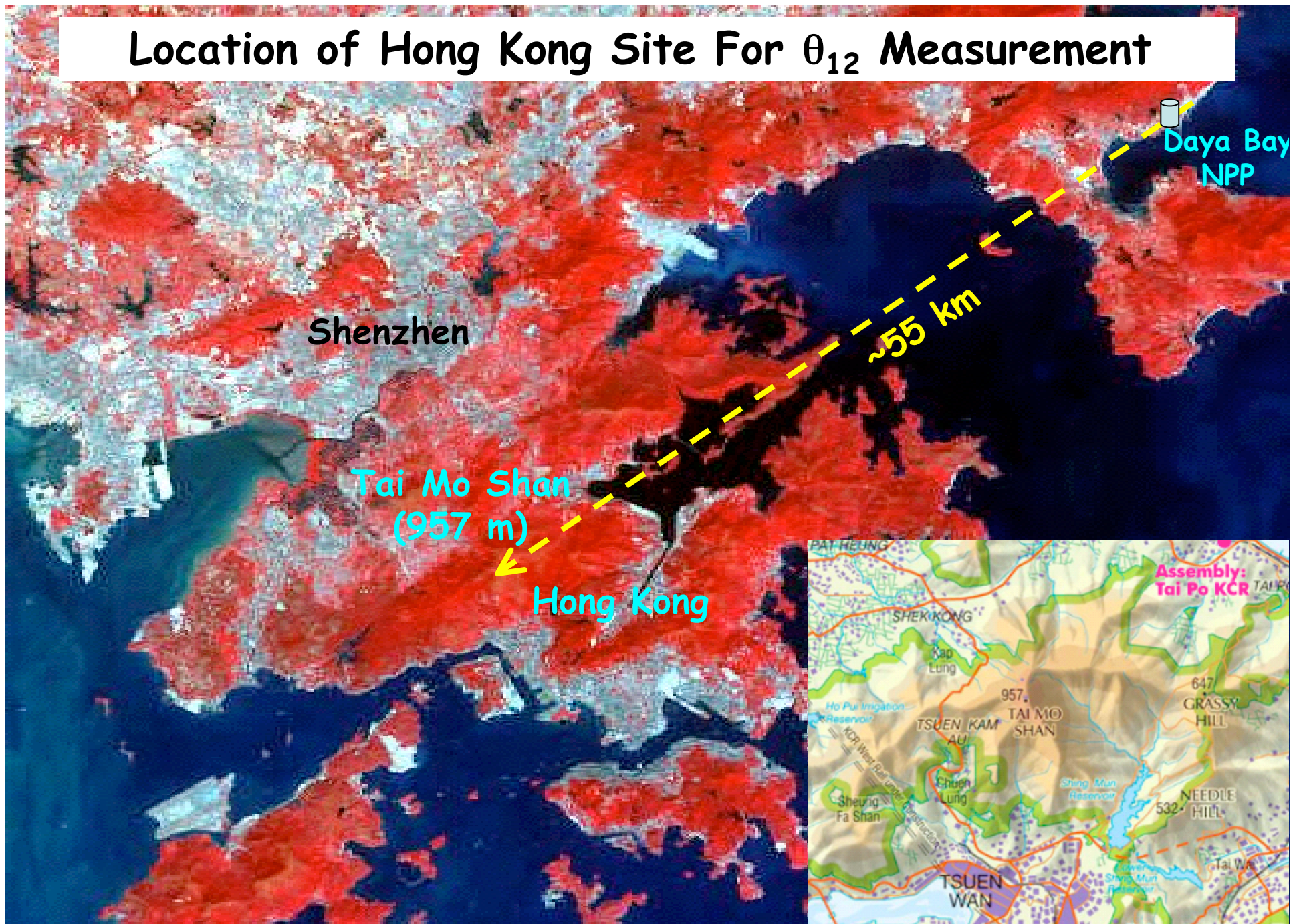
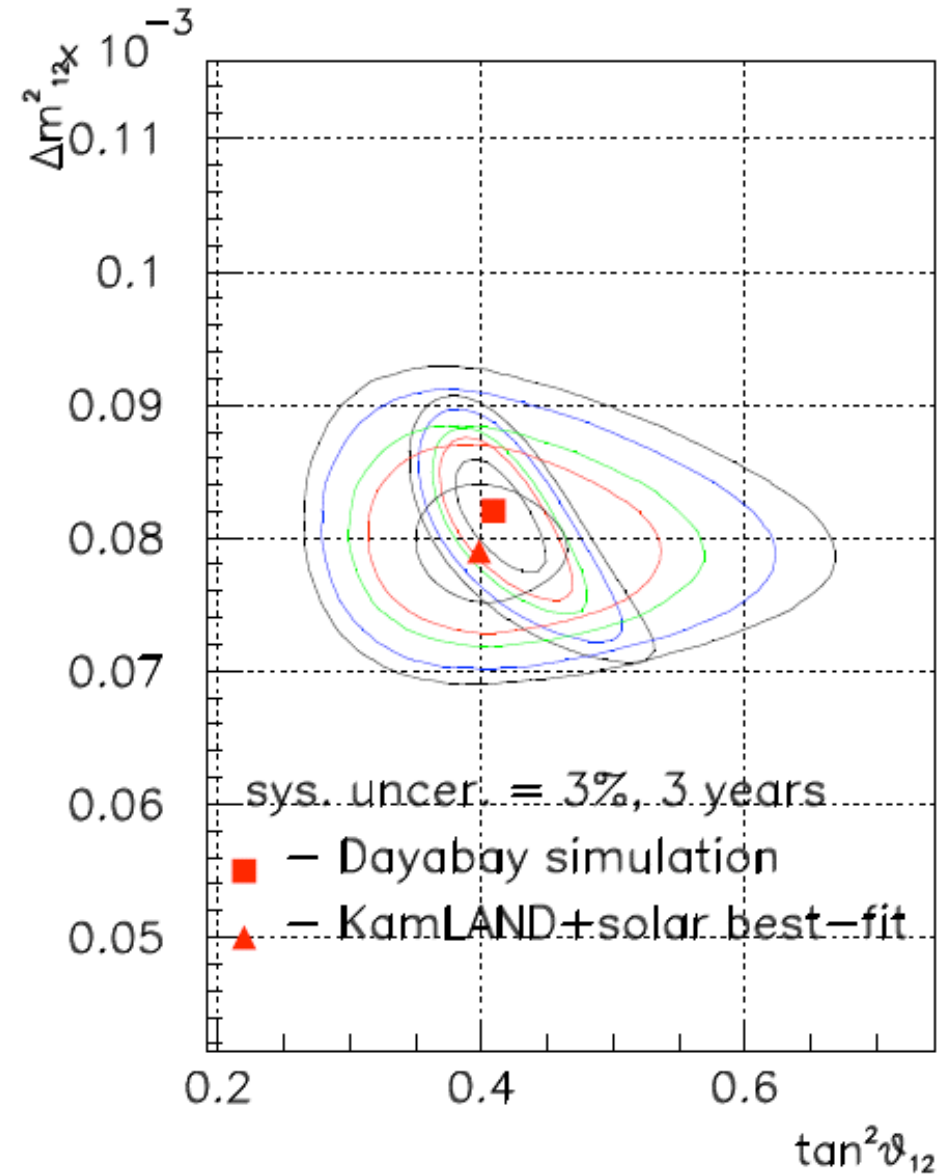# Precision of θ_{12} With The Daya Bay Facility

Inputs:

• Thermal power = 17.4 GW

• Baseline = 55 km

• Target mass = ~ 500 ton LS

• Mixing parameters:

$\sin^2 2\theta_{12} = 0.825$

$\sin^2 2\theta_{13} = 0.1$

$\Delta m^2_{12} = 8.2 \times 10^{-5}$ eV^2

$\Delta m^2_{13} = 2.5 \times 10^{-3}$ eV^2

Summary and Prospects

- The Daya Bay nuclear power facility in China and the mountainous topology in the vicinity offer an excellent opportunity for carrying out a reactor neutrino program using horizontal tunnels.

- The Daya Bay experiment has excellent potential to reach a sensitivity of 0.01 for $\sin^2 2\theta_{13}$.

- The three Chinese funding agencies are discussing cost-sharing of a request of RMB$200 million.

- The US team is waiting for the NuSAG's decision.

- Will complete detailed design of detectors, tunnels and underground facilities in 2006.

- Plan to commission the Fast Deployment scheme in 2007-2008, and Full Operation in 2009.

- **Welcome more collaborators to join.**